D. K. Ferry
W. A. Porter

Microwave Emission and High-frequency Oscillations in n-Type InSb*

Abstract: Microwave emission from n-InSb at 77°K in the presence of electric and magnetic fields was studied. Rectangular InSb samples were cut so that the long dimension and the applied electric field were parallel to one of the crystallographic axes ⟨100⟩, ⟨110⟩, or ⟨111⟩ and so that the position of all other axes was known. It was observed that instabilities in the voltage across the InSb sample accompanied the microwave emission and that, for a limited range of electric and magnetic fields, these instabilities were in the form of coherent oscillations. Both effects showed their lowest electric field thresholds when the magnetic field was parallel to one, but not a specific one, of the crystallographic axes. Both effects were shown to occur at electric fields below those expected for an electron-hole plasma and a close correspondence between the two effects was demonstrated.

Introduction

Microwave emission from indium antimonide has been observed by several investigators.[1-4] This emission has been observed for electric fields above that required for impact ionization,[1,2] as well as fields below that level.[3,4] These two regimes have generally been referred to as the high-field and low-field microwave emission. The various reports of emission seldom agree in details other than the observance of microwave emission. This paper presents studies of the microwave emission which, it is felt, clarify some of the discrepancies in threshold dependence on magnetic field orientation as well as connect the low- and high-field regimes.

The samples, with carrier concentration of 2.5×10^{14} cm^{-3} and mobility at 77°K of 5.6×10^5 $cm^2/V\text{-}sec$, were prepared from 1.0 mm thick slices of n-type InSb cut with a ⟨110⟩ crystallographic plane. X-ray diffraction was used to orient these slices. Samples in the form of rectangular bars 0.5 mm square and from 3.0 mm to 13.0 mm in length were cut from these slices. These bars were cut so that the long dimension was parallel to the ⟨100⟩, ⟨110⟩, or ⟨111⟩ crystallographic direction. Ohmic contacts were applied with tin solder.

The samples were mounted as the center conductor in a coaxial insertion unit (Fig. 1) and immersed in liquid nitrogen. Mounted in this manner, the current and electric field were parallel to one of the axes (see Fig. 2) and the magnetic field could be rotated in the plane

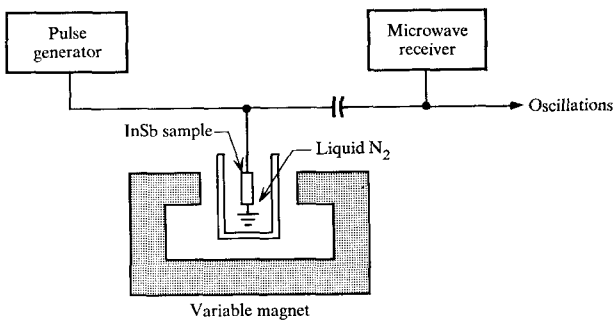

Figure 1 Experimental apparatus. The details of the apparatus are given in the text.

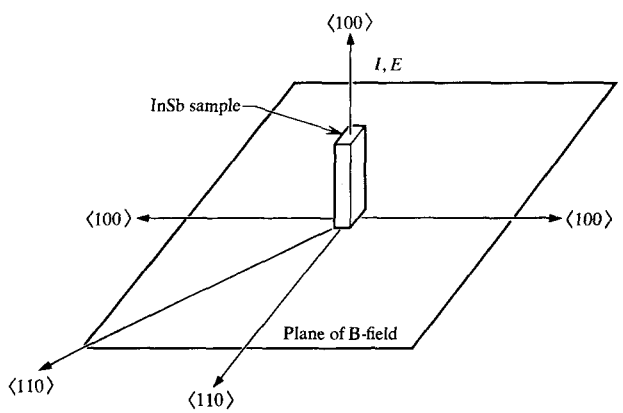

Figure 2 Sample orientation for producing polar plots by rotation of the magnetic field in the plane perpendicular to the sample. Some of the crystallographic axes for a particular sample are shown.

* This work was supported in part by the National Science Foundation.
The authors are in the Department of Electrical Engineering, Texas Technological College, Lubbock, Texas.

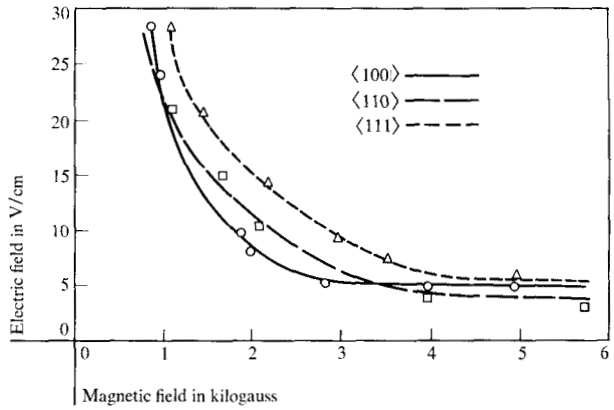

Figure 3 Threshold curves for the microwave emission for samples of various crystallographic orientations for a transverse magnetic field.

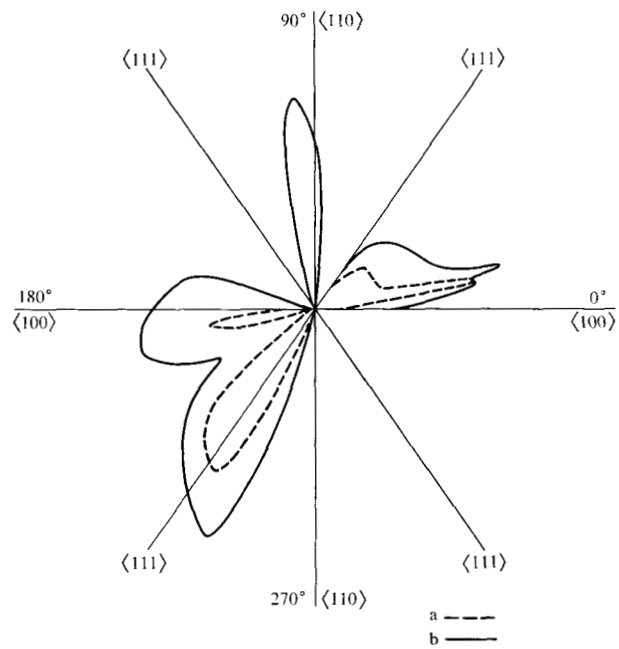

Figure 4 Microwave emission polar plot for a ⟨110⟩ sample. Curve (a) is for an electric field of 31.3 V/cm and (b) is for 40.2 V/cm. The transverse magnetic field is 1.87 kG.

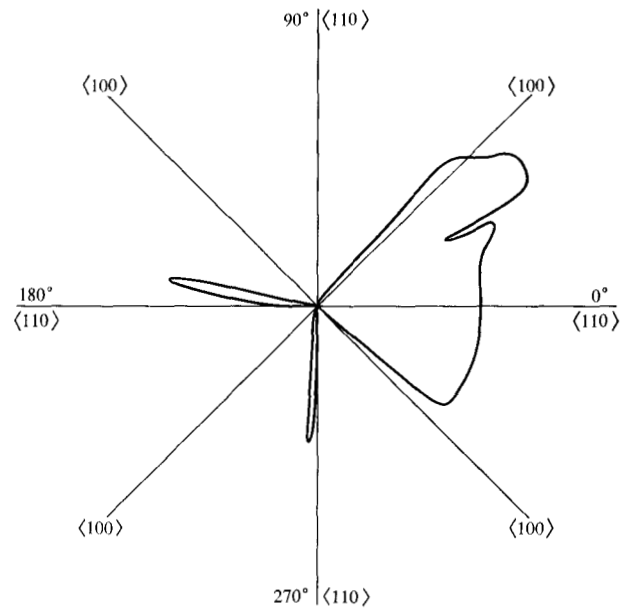

Figure 5 Microwave emission polar plot for a ⟨100⟩ sample for an electric field of 17.5 V/cm and a magnetic field of 1.87 kG. Emission occurs for B along three of the four ⟨110⟩ directions in the plane.

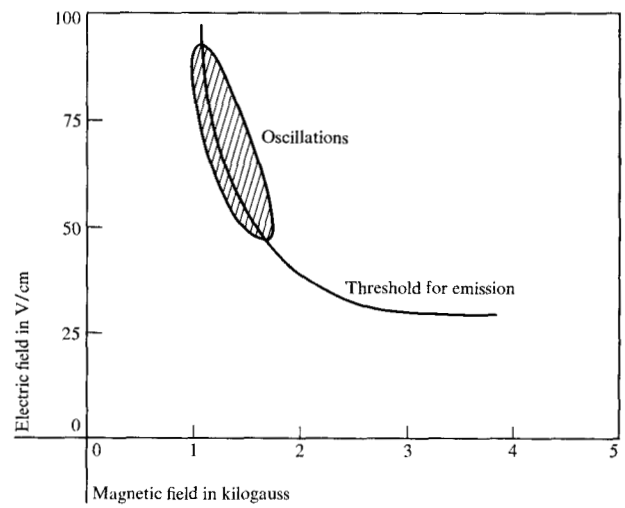

Figure 6 Field regime for producing the megahertz oscillations. The voltage oscillations occur in the cross-hatched region. The threshold for microwave emission is shown for comparison.

perpendicular to this axis, this plane containing certain of the crystallographic axes. When the magnetic field was rotated in this plane, polar plots were produced showing one of the parameters measured (e.g. amplitude of microwave emission) as a function of magnetic field orientation. Relevant crystallographic axes are shown in these polar plots also.

The equipment shown in Fig. 1 was used to study the voltage instabilities in InSb. The pulse generator had an output impedance of 50Ω and supplied rectangular pulses with a duration of from 2 to 100 pulses per second. The heterodyne microwave receiver had a sensitivity of −75 dBm and a frequency response of 1 to 2 GHz. The output of the receiver was a voltage proportional to the input microwave power. This output and the voltage pulse applied across the InSb sample were displayed on an oscilloscope. The voltage instabilities were observed in these pulses. The constant magnetic field was supplied by an electromagnet having a

maximum field intensity of 6 kilogauss. The magnet could be rotated in the horizontal plane.

Microwave emission

For samples parallel to each of the three principal crystallographic directions, the combination of electric and magnetic fields required to initiate microwave emission was determined. Shown in Fig. 3 are the threshold curves obtained. Microwave emission occurs for values of E and B above and to the right of the curves in each case. As may be seen, there is only a small variation among the three curves.

Polar plots, as mentioned, were obtained for the amplitude of microwave power as a function of magnetic-field orientation. Figure 4 shows polar plots of a sample for two different electric-field strengths. As can be seen, emission is strongest along certain of the axes. This also indicates a lower threshold along these axes. As the electric field is increased, emission is observed for a more uniform range of angles, but anisotropy is still strong. Figure 5 shows a similar polar plot. Notice that three of the four $\langle 110 \rangle$ axes show strong emission but that the fourth does not. These and similar observations suggest that the microwave emission has a lower threshold when the magnetic field is oriented parallel to one of the crystallographic axes. However, no uniform preferred axis is apparent, and not all of the equivalent axes are equivalently preferred. These observations hold for all samples examined, regardless of length or surface condition. Holding the electric-field constant and varying the magnetic field produces roughly similar results.

Megahertz oscillations

In conjunction with these studies, instabilities in the voltage across the samples were observed. For certain combinations of electric and magnetic field, these instabilities were in the form of coherent megahertz oscillations ranging in frequency from 1.8 MHz to beyond 170 MHz. Figure 6 shows the range of fields producing oscillations, compared with the threshold for microwave emission for a typical sample. Values of electric and magnetic field higher than these generally resulted in incoherent voltage instabilities while those lower produced nothing. The frequency of these oscillations was a function of the electric and magnetic field strength and of the orientation of the sample. Most commonly, the frequency was observed to change in a continuous manner with variation of any of these parameters.

Three other nonlinear methods of frequency change deserve mention. In the first of these, the frequency suddenly changed to some other value as one of the parameters (e.g., electric field) was varied continuously. At the critical point, either frequency might occur for successive voltage pulses, with no change in field strength or position. In the second (shown in Fig. 7), the oscillations became incoherent with increasing electric field and after a turbulent period, the coherent oscillations reappeared, with a greatly different frequency. Figure 8 shows the last method of frequency change, that of harmonic mixing. The wave form changes continuously from one frequency to another with changes in electric field.

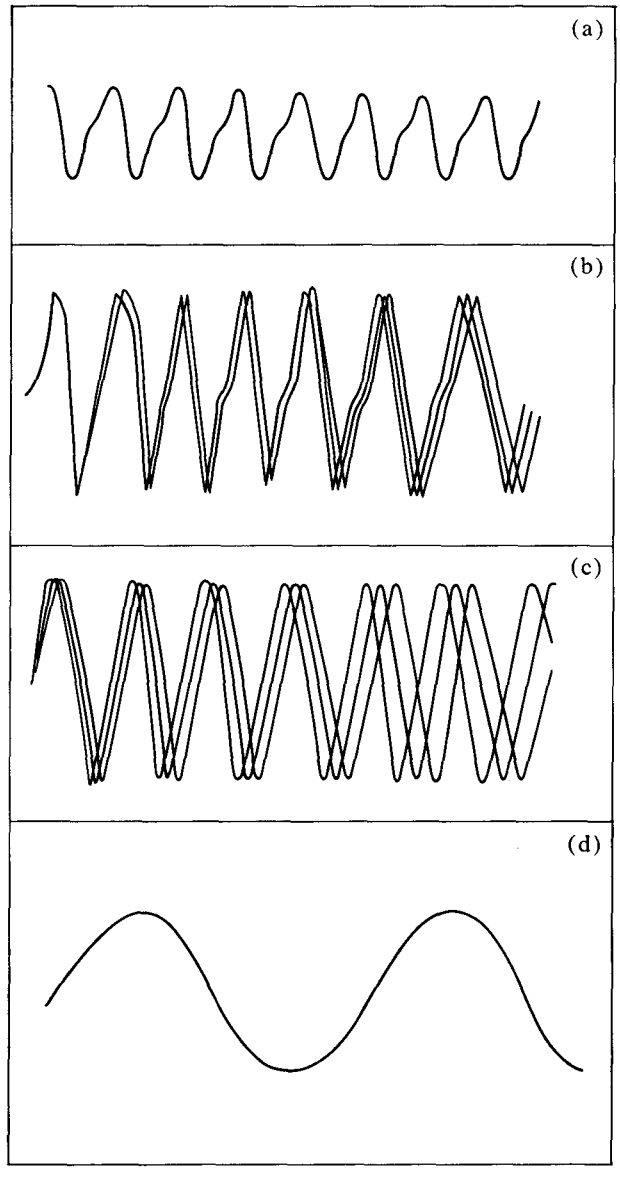

Figure 7 Oscillations showing a frequency change after a period of turbulence. Part (a) is for $E = 22$ V/cm, $f = 8.3$ MHz; (b) is for $E = 30$ V/cm; (c) for $E = 33$ V/cm; (d) for $E = 50$ V/cm, $f = 1.8$ MHz.

A study was made of the effect of magnetic field position on oscillation frequency for various combinations of electric and magnetic field strengths. Figure 9 shows a

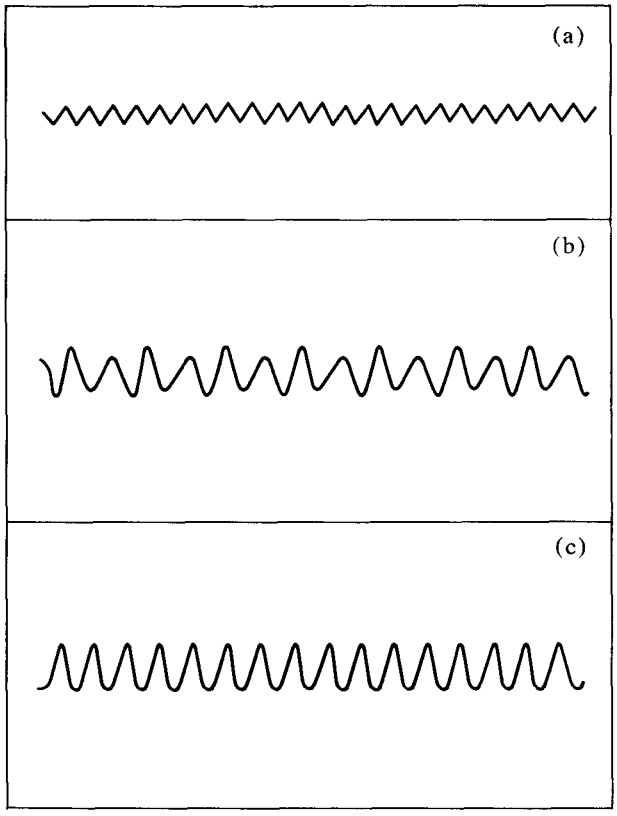

Figure 8 Oscillations showing a frequency change by harmonic mixing. Part (a) is for $E = 23$ V/cm, $f = 24$ MHz; (b) for $E = 28.5$ V/cm; (c) for $E = 29$ V/cm, $f = 16$ MHz.

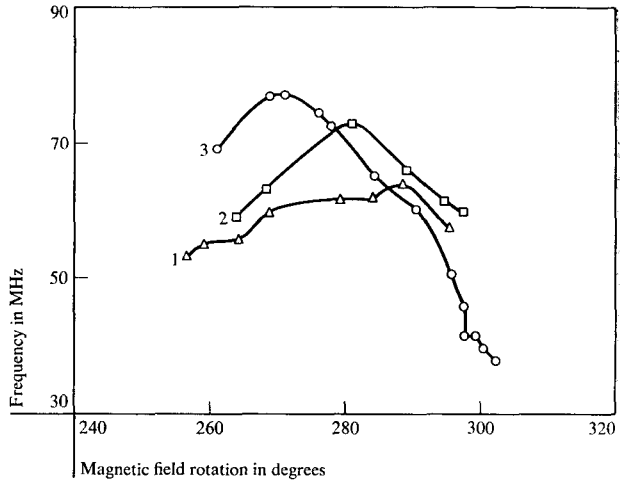

Figure 9 Variation of the frequency as the applied magnetic field is rotated. The values of the applied electric and magnetic fields are the parameters: (1) $E = 26.3$ V/cm, $B = 780$ G, (2) $E = 26.3$ V/cm, $B = 880$ G, (3) $E = 32.1$ V/cm, $B = 880$ G.

portion of the data for one of the samples examined. Where no results are indicated, the voltage instabilities were not present or were incoherent. These data show that where the magnetic field is constant and the electric fields are different (curves 2 and 3) the higher frequency always corresponds to the lower electric field strength. No similarly consistent results can be reported for the case of a constant electric field and different magnetic fields (curves 1 and 3). The average change in frequency for different electric fields for several samples was about 1 MHz/V/cm change in electric field. The point where different magnetic fields produce the same frequency (e.g., where curves 1 and 3 cross in Fig. 9) was often at an angle for which a maximum of microwave emission was observed.

It is possible that there are two separate regimes of oscillation present. The lower regime is composed of frequencies from 1.8 MHz to about 18 MHz while the higher regime is composed of frequencies from 16 MHz to beyond 170 MHz. Two facts suggest this possibility. First, all samples observed exhibited the higher regime while fewer than half the samples exhibited the lower. Second, on a few occasions, both regimes were seen together in the form of one oscillation superimposed on the other. In all such cases, a harmonic relation existed between the two frequencies.

Polar plots were made showing the amplitude of oscillation as a function of magnetic field position. One such polar plot, obtained for the same sample as that used for Fig. 4, showed a polar plot markedly similar to Fig. 4. It is difficult to make an exact comparison between microwave and megahertz oscillation amplitude polar plots because the noise-like microwave emission does not suffer from the problem of severely restricted E and B field ranges. It is believed that voltage instabilities precede the appearance of microwave emission in all cases, but that only for a small range of electric and magnetic fields do these instabilities take the form of coherent oscillations. Also, these coherent oscillations are more often observed where the microwave emission thresholds are lower, i.e., along certain crystallographic axes, and less often where the thresholds are higher, the region between axes. The fact that these oscillations invariably break up into noise for sufficiently high fields suggests that they are closely related to the microwave emission.

Conclusions

The observed anisotropy of the microwave emission for the rotation of the transverse magnetic field can easily explain the reported discrepancies in emission thresholds. In every case in which the magnetic field was oriented to optimize the emission, thresholds were lower for transverse magnetic fields than for longitudinal fields. However, if the field were not optimized in orientation angle, it is apparent that emission would appear at lower

thresholds for a longitudinal orientation. The origin of this anisotropy is still unexplained.

The megahertz oscillations reported by the authors[5] are clearly very similar to those of the helical instability reported by Ancker-Johnson[6] for p-type InSb in the presence of an electron-hole plasma. The frequency ranges are similar and the methods of frequency change are identical. These oscillations also appear similar to those reported in lesser detail by Toda[2] for n-type InSb in the presence of a plasma. Neither of these reports considered the possibility of a relation to microwave emission. The oscillations reported here break up into a noise-like current oscillation similar to that reported in connection with microwave emission by Larrabee and Hicinbothem.[7] This report provides a link between these early observations of current oscillations and those of microwave emission. Microwave emission is believed to be independent of the existence of an electron-hole plasma.[3] The close correspondence between the two effects shown here suggests that microwave emission at low fields is identical in nature to that at high fields and is probably dependent on the prior existence of instabilities in the voltage across the sample. This dependence suggests that a common mechanism is responsible for both effects. If the microwave emission is indeed independent of the existence of an electron-hole plasma, then the plasma-based explanations which have been proposed so far[8,9] are clearly inadequate to explain the instability. It is possible, though, that a contact[10] or inhomogeneity effect can cause a localized high-field region leading to impact ionization in a localized area. The anisotropy of the microwave emission can be interpreted in this light if the current shows a preferred direction along crystalline defects or direction dependent inhomogeneities such as impurity segregation. If a localized high-field region is responsible for the emission, then it is doubtful that surface related instabilities are involved.[9]

The possible dependence on localized high-field regions due to unpredictable defects or inhomogeneities could explain the discrepancies among earlier reported observations. This report provides a link between early observations of current oscillations, both coherent and incoherent, and microwave emission. Whatever the underlying mechanism, it is possible that all these instabilities are related.

References

1. R. D. Larrabee and W. A. Hicinbothem, Jr., *Proceedings of Symposium on Plasma Effects in Solids,* Paris, 1964.
2. M. Toda, *Jap. J. Appl. Phys.* **2,** 776 (1963).
3. S. J. Buchsbaum, A. G. Chynoweth and W. L. Feldmann, *Appl. Phys. Lett.* **6,** 67 (1965).
4. D. K. Ferry, R. W. Young and A. A. Dougal, *Bul. Am. Phys. Soc., Ser. II,* **10,** p. 594 (1965).
5. W. A. Porter and D. K. Ferry, *Proc. IEEE* **56,** 1625 (1965).
6. B. Ancker-Johnson, *Proceedings of Symposium on Plasma Effects in Solids,* Paris, 1964.
7. R. D. Larrabee and W. A. Hicinbothem, *IEEE Trans. Electron Devices* **ED-13,** 121 (1966).
8. M. C. Steele, *Proceedings of Symposium on Plasma Effects in Solids,* Paris, 1964.
9. B. Ancker-Johnson, *J. Appl. Phys.* **39,** 3365 (1968).
10. A. Thompson and G. Kino, *IBM J. Res. Develop.* **13,** 616 (1969, this issue).

Received April 8, 1969